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Proposal No. ES-20793

LINEAR PHASOLVER

194/63

11 April 1963

Prepared for

AIR FORCE HEADQUARTERS
Washington, D.C.

By

[redacted] STAT

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SUMMARY

The objectives of this program are to develop and demonstrate a system for measuring linear movement with a resolution and accuracy of one micron or less.
STAT [redacted] proposes to accomplish these objectives by developing a linear Phasolver*, based on the already proven principles of the Phasolver as used in circular applications.

The Phasolver is a precision device which accurately converts minute increments of mechanical motion to large electrical phase-shift information. The resultant electrical phase shift can be easily processed and digitized by the associated electronic equipment to provide a highly accurate readout. It is well suited to both linear and rotary applications.

The Phasolver consists of a pair of dimensionally stable nonconductive plates. Each plate carries a conductive pattern of metal film. The plates are mounted so that the two patterns face each other, closely spaced. The pattern on one plate (driver) is provided with four sinusoidal input signals which bear a quadrature phase relationship (0-, 90-, 180-, and 270-degree displacement). These signals are electrostatically coupled to the opposing (coupler) pattern. A minute change in the relative positioning of the driver with respect to the coupler varies the relative amplitudes of the quadrature signals coupled from the driver to the coupler pattern. The vector summation of the coupled signals constitutes the Phasolver output. Because of the quadrature relationship of the drive signals, the output is a constant-amplitude sinusoidal signal which varies in phase in response to changes in the relative positioning of the driver and coupler plates.

In a completely operational system, the associated electronics, in conjunction with the Phasolver transducer, will provide a unique readout for any position over the entire range of measurement. This readout, because of the method by which linear displacement is converted to electrical information, will not be lost due to momentary loss of power.

The research and development program proposed in this document will be accomplished in two phases.

a. PHASE I. - During Phase I of the program, a feasibility model of a linear Phasolver will be developed and demonstrated to verify that the basic Phasolver principles can be applied to measurement of linear displacements.

b. PHASE II. - During Phase II of the program, a developmental model of a linear Phasolver will be designed, fabricated, and tested. The design accuracy goal for the Phase II linear Phasolver will be one micron with a design resolution goal of approximentely one-quarter micron in a travel of not less than 10 inches.

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*Trademark of [redacted]

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The schedules of the tasks to be accomplished during Phases I and II are provided in Section 4 of this proposal. [redacted] foresees no major problems in meeting the proposed schedules. STAT

Budgeting information is supplied as a separate enclosure attached to the letter of transmittal.

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SECTION 1

INTRODUCTION

1-1. PROGRAM OBJECTIVES

This document proposes and describes an applied research program for developing and demonstrating the feasibility of a system for making linear measurements with a resolution and accuracy of one micron or less. This linear Phasolver program will be accomplished in two phases and will be based upon the proven principles of the Phasolver as used in circular applications.

1-2. WORK STATEMENTS

[redacted] proposes to perform the following work during Phases I and II of this program:

a. PHASE I. - [redacted] will perform a feasibility demonstration of a linear Phasolver to verify that the basic Phasolver principles can be applied to measurement of linear displacements. The demonstration will include, but not necessarily be limited to, tests which verify a monotonically increasing count with displacement.

b. PHASE II. - [redacted] will design, fabricate, and test a developmental model of a linear Phasolver. The design accuracy goal will be ± 1.0 micron with a design resolution goal of about 0.25 micron in a travel of not less than 10 inches. Tests will include, but not necessarily be limited to, accuracy and resolution tests over the specified travel at laboratory ambient temperature conditions.

1-3. REPORTS

a. MONTHLY STATUS REPORTS. - During the period of performance of the contract, [redacted] will submit monthly status reports. These reports will be postmarked on or before the tenth day of the month succeeding the report period. Progress photography will be included in these reports.

b. SUMMARY REPORT. - Prior to the completion of the contract, [redacted] will submit a final summary report. This report will include, but not necessarily be limited to, the following: 1) a summary of work accomplished; 2) detailed design considerations; 3) test data; 4) test equipment documentation, including test error analysis; 5) discussions of test results; 6) problem areas encountered; and 7) recommendations for future work.

1-4. DELIVERABLE ITEMS

In addition to the reports described in paragraph 1-3, the items described in the following subparagraphs will be delivered at the conclusion of Phases I and II.

a. PHASE I. - At the conclusion of Phase I, the following items will be delivered to the customer or his designee: 1) the electronics designed and fabricated during this phase and 2) all test results obtained. The glass plates used in Phase I
STAT are the property of [redacted] and are not considered as deliverable items. The commercial counters used in digitizing the processed analog information
STAT are the property of [redacted] and are not considered as deliverable items.

b. PHASE II. - At the conclusion of Phase II of the program, the developmental linear Phasolver used in Phase II will be delivered the the customer or his designee. This includes the test fixtures, glass plates, and the electronics designed and fabricated during Phase I for use in both Phase I and Phase II. The commercial counters used in digitizing the processed analog information are the property of [redacted] STAT
STAT [redacted] and are not considered as deliverable items.

SECTION 2

TECHNICAL DESCRIPTION

2-1. PHASOLVER PRINCIPLES

The Phasolver is a precision device which accurately converts minute increments of mechanical motion into large increments of electrical phase-shift information. The resultant electrical phase shift can be either translated into elapsed-time indication or digitized to provide an accurate readout. The Phasolver can be utilized to measure either linear or rotational displacement.

2-2. PHYSICAL DESCRIPTION

The linear Phasolver consists of two dimensionally stable plates which are fabricated of nonconductive material. Parallel bands of conductive material are applied to both plates and processed to provide the patterns which enable the Phasolver to perform its function. The patterns on the two plates are of different configurations and perform different functions. (See figure 2-1) The patterns on one plate are utilized as the signal-drive element in the electrostatic coupling process and are designated as drive patterns. The patterns on the second plate are utilized as the coupling element in the electrostatic process and are designated as the coupler patterns.

a. DRIVER PATTERNS. - The driver plate utilizes two sets of drive patterns - fine and coarse. Both are formed by a sinusoidal nonconductive separating area which divides each band of conductive material into two conjugate patterns.

(1) Fine Driver Pattern. - The fine driver pattern consists of two bands of sinusoidal conjugate patterns which are physically phase displaced by 90 degrees. Therefore, four patterns are provided to accommodate the required four quadrature drive signals. The pattern is extremely fine. One cycle (pole-pair) is approximately 0.040 inch in length and a drive pattern for a linear Phasolver, designed to measure 10 inches of linear displacement, utilizes approximately 256 pole-pairs.

(2) Coarse Driver Pattern. - The coarse driver pattern differs only in the number of pole-pairs. This pattern is utilized for a coarse measurement of linear displacement to resolve ambiguity and establish a unique output; therefore it requires one pole-pair extending over the entire length of the linear range of motion.

b. COUPLER PATTERNS. - The coupler patterns (coarse and fine) consist of alternate bars of conductive material and spaces of nonconductive material. The width of the bars and spaces are equal and are of the same dimension as one-half wavelength of the associated driver pattern.

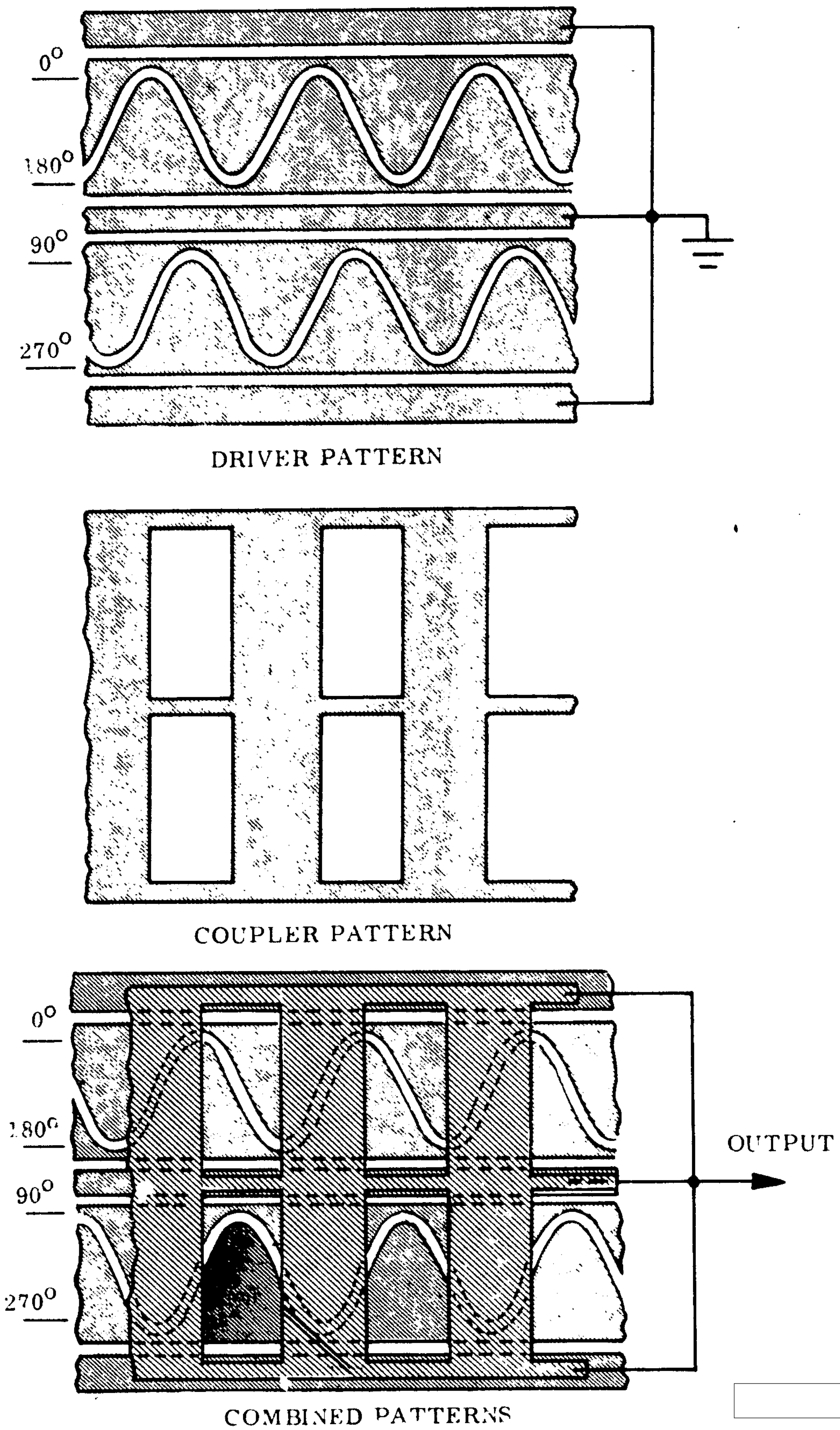

Figure 2-1. Phasolver Coupler and Driver Patterns

2-3. FUNCTIONAL DESCRIPTION

The generation of phase-shift information in response to a change in the relative position of the driver with respect to the coupler is illustrated in figure 2-2. This illustration shows only one sinusoidal segment (pole-pair) and follows the motion of the coupler-pattern bar over this pole-pair. At each progressive position of the coupler bar, corresponding diagrams are shown for the vector summation of the output signal.

The four drive patterns are each excited by one of the four sinusoidal quadrature drive signals. The frequencies are the same but are displaced from each other by a 90-degree phase difference.

The driver and coupler plates are mounted so that the two patterns face each other, closely spaced. The relative amplitude of the drive signal which is coupled from each driver pattern is a function of the area of the driver pattern encompassed by the coupler-pattern bar. The output provided by the coupler pattern at any position is the vector sum of the coupled drive signals.

A minute change in the relative positioning of the driver with respect to the coupler varies the relative amplitude of the quadrature signals coupled from the driver to the coupler pattern. This results in a change in the vector summation and causes a change of phase in the constant-amplitude sinusoidal output signal. This phase shift increases continuously from 0 to 360 degrees as the moving element moves a distance equal to one sinusoidal driver pattern. (See figure 2-2.) Because of the symmetry in arrangement of the pattern-pairs and coupler bars of the fine patterns, an average output of all pattern-pairs is obtained. This averaging effect results in minimizing errors introduced because of nonlinear pattern-pair spacing.

2-4. PHASOLVER ADVANTAGES

The most significant advantages offered by the Phasolver system of analog measurement are the following:

a. No information is lost when momentary power failure occurs.

b. There is no gearing. Phasolver plates are directly connected to the moving and reference members.

c. The Phasolver transducer can be formed in the size and shape required for measuring linear or rotational movement and can be mounted around a moving shaft.

d. High speed cannot damage the plates.

e. The Phasolver is not affected by ferrous metals or stray magnetic fields. All coupling is electrostatic.

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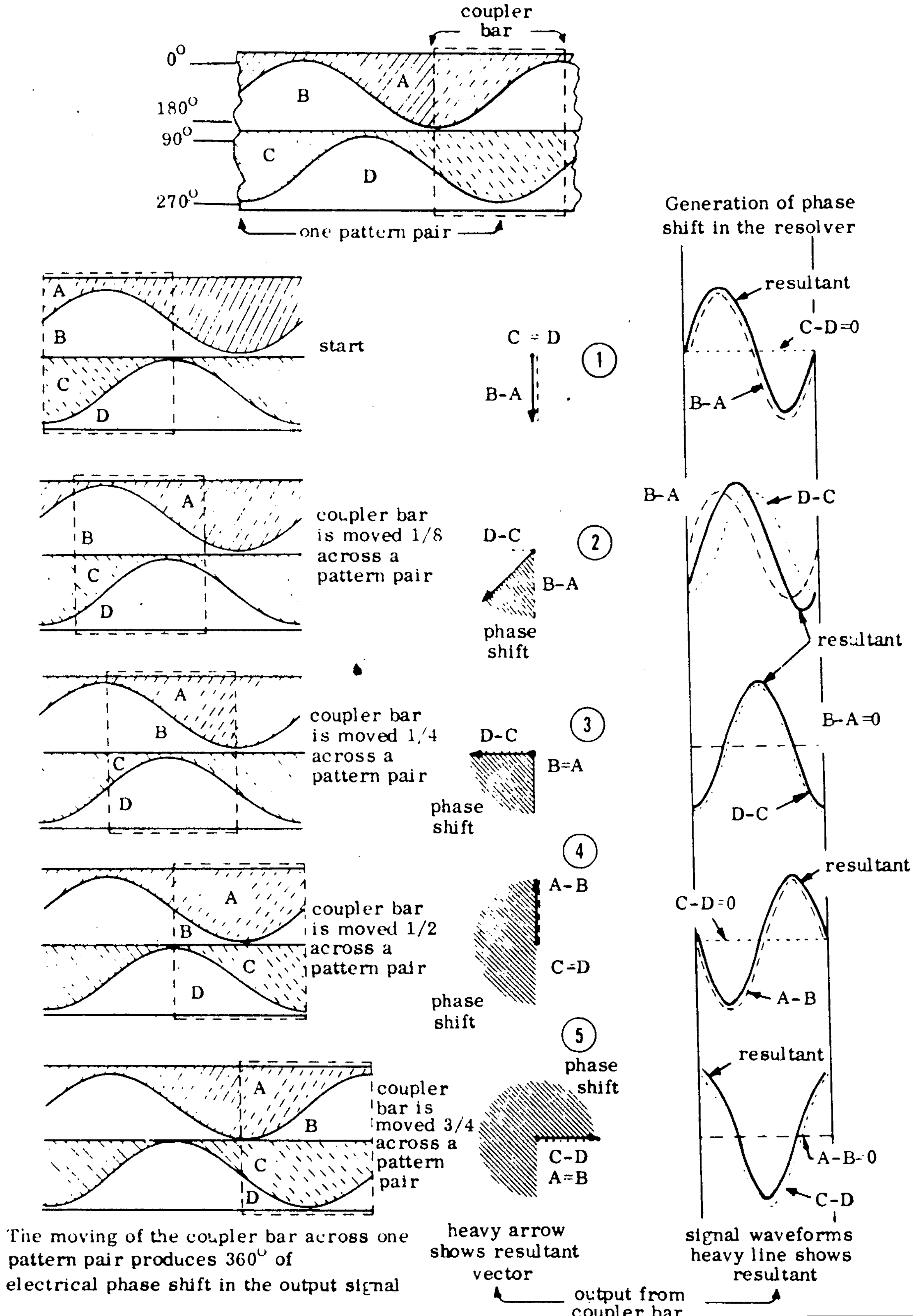

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Figure 2-2. Vector Analysis of Phase Shift in a Phasolver

f. Outputs are uniquely established; no accumulators are required.

g. Resolution can be improved by changing the Phasolver electronics, not the Phasolver itself, thus eliminating the need for dismantling the equipment.

h. A high degree of accuracy can be obtained with the Phasolver due to the averaging effect inherent in its multiple-pole-pair configuration.

i. Readout can be obtained in either digital, binary, or analog form.

2-5. ELECTRONIC REQUIREMENTS. - The electronics required for the linear Phasolver transducer are similar to the electronics used in all other Phasolver applications (figure 2-3). Drive frequencies must be generated and the phase shift information from the Phasolver must be processed for the desired readout.

2-6. PHASE I DESIGN INFORMATION

a. INTRODUCTION. - The task specified for Phase I of this program is to provide a feasibility model of a linear Phasolver to demonstrate that it is capable of measuring linear movement by the proposed method. Accuracy of measurement is not required; however, ability to achieve a monotonically increasing count for increasing increments of linear motion will be demonstrated.

Existing linear Phasolver elements will be utilized in Phase I, and stable electronics will be fabricated using proven circuit design. The electronics package used in Phase I will have the necessary phase stability characteristics for the Phase II accuracy and resolution requirements and will be used in Phase II tests.

b. MECHANICAL DESIGN. - The driver plate will be mounted on the table of a machine tool (mill, surface grinder, etc) with the pattern surface facing upward. The coupler plate will be mounted in the tool holder with its pattern surface facing, and closely spaced from, the driver pattern. Relative motion of the plates will be monitored by a dial indicator having a 1-inch throw.

c. ELECTRONIC DESIGN. - The electronics will supply the drive signals to the driver pattern and will process the output signal from the coupler pattern. The processed signals will be digitized and the readout will demonstrate that a monotonically increasing count will be achieved for both the fine and coarse patterns in response to relative linear movement of the driver plate with respect to the coupler plate.

2-7. PHASE II DESIGN INFORMATION

a. INTRODUCTION. - The proposed equipment will meet the performance requirements if a resolution and accuracy of one micron or less is achieved; however, for the purpose of detecting and analyzing errors, it is advantageous to have a resolution

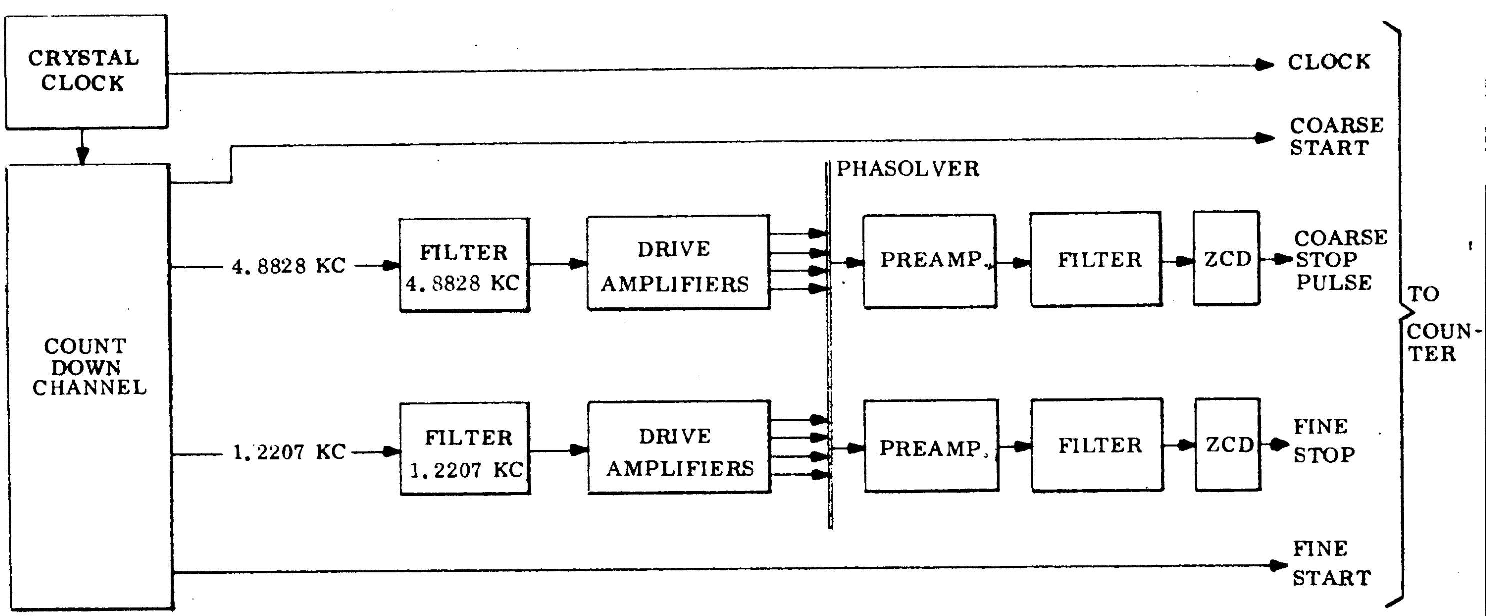

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Figure 2-3. Linear Phasolver System, Phases I and II; Block Diagram finer than the least permissible error. For this reason, we plan to provide a resolution of slightly less than one-quarter micron.

Our electronics permit us to divide a single pole-pair into 4096 parts. Therefore, taking a pole-pair as 0.0400 inch and dividing by 4096, the linear value of each count will be 9.765 microinches (0.248 microns) per count. The problem of resolving the ambiguity in the fine count so that the specific 0.040-inch increment can be identified can be readily solved; therefore, we propose to utilize only a fine track. This will provide substantial saving in the cost of the project.

For clarification of the following discussion, refer to the layout shown in figure A-1 of Appendix A. The moving member is the shorter of the two and is the driver. Provided that there is no difference in scale between the two patterns that exceeds one pole-pair (0.040 inch, nominal) over the length of the driver, and further provided that the driver ends symmetrically, it is possible to show that the driver behaves like a single line at its midpoint; therefore, the scale of the device is controlled by the coupler. Interchanging the position of the driver and coupler, or the selection of which shall be the moving element, does not affect the result. The longer of the two patterns controls the scale accuracy of the device. It should be understood, however, that this applies only to positions exactly n pole-pairs apart. The errors within any pole-pair are controlled by a large number of variables reflecting the accuracy of both the patterns and the electronics. Because it is easier to generate a coupler accurately and also easier to measure the results, the coupler will be made the longer of the two patterns.

b. MECHANICAL DESIGN. - The layout of the equipment to be used in Phase II of this program is illustrated in figure A-1 of Appendix A. To avoid the difficulties involved in building (or the cost of buying) ways of jig-borer quality, no auxiliary guiding or bearing surfaces will be used excepting item 1, a glass "guide." The "driver," item 5, will slide with little or no lubrication in the corner made by the guide and the coupler. The intention is to set the driver approximately by hand and to make the fine adjustment with an 80-pitch screw. Should it prove necessary, spring-loaded bearings can be attached to the box to keep the driver securely in the corner.

(1) Setting. - The driver will be set against gage blocks. View A-A shows the arrangement. The surface of the anvil (item 8) has been reduced to prevent the formation of an air film. The anvil itself is mounted by an elastic pantograph so that deflection does not change its attitude and introduce a cosine error. (Note: the anvil face will be ground after assembly.)

The suspension of the anvil is arranged so that the orthogonal motion induced by deflection in the direction of driver motion will tend to pull the gage block and the end of the driver toward the guide, thus guaranteeing correct alignment. On the other side of the gage block, part of a sphere will be bonded to the end of the driver. This removes the requirement for a "perfect" surface on the end of the driver, solves the air film problem, and minimizes the requirements of cleanliness.

[redacted]

The suspension of the anvil will act as a spring as well as a pantograph. Adjustable stops have been provided to protect both the leaf springs and the electronic gage head. With the electronic gage head in place, it will be possible to measure the force at the null (arbitrary zero) position of the gage. Since the resolution of the gage is one microinch, and we know by experience that an 80-pitch screw can be set to one microinch we can be sure that the pressure on the gage blocks can be, for all practical purposes, exactly equal for all settings of the Phasolver.

(2) Range. - The layout shows a design intended to have a total range of 10 inches. Since it is not practical to have an 80-pitch screw 10 inches long a sliding clamp will carry the 1/4-80 screw used for fine adjustment. The rail on which this clamp slides is attached to the box rather than to the glass parts of the Phasolver. Setscrews (not shown) will be used to prevent relative motion between the box and the glass parts.

(3) Gap. - Utilizing a gap which is as narrow as possible will increase the signal-to-noise ratio, and minimize the fringe effects. The lower limit on gap is imposed, not by the dielectric strength of air or dry nitrogen, but by practical accuracy of manufacture and mounting, including the touchup now required by present techniques of disk manufacture. In the case of a linear Phasolver, we have much greater latitude in placing the contacts, and can probably avoid the use of touchup altogether. This should permit us to reduce the separation between the two plates to a dimension of from 0.5 to 2 mils rather than the 3.5-mil separation now used for rotating disks.

(4) Potential Errors. - A list of known error components are presented in table 2-1. This table includes the type, probable cause, and comments.

A circular Phasolver has a fixed number of pole-pairs and the determination of this number is not modified by the effect of temperature on the function of the properties of the materials of which it is made. However, a linear Phasolver develops the same scale problems that affect every other measuring device that is dependent on a material standard In addition to the scale error in the standard (in this case, the pattern) a second scale error will be introduced by changes in temperature.

A permissible error of one micron over 10 inches means a total error from all causes of 4-microinches per inch. The entire scale error permissible would be used up by temperature change of one degree if the substrate is borosilicate ("Pyrex") glass. But the substrate material is not the limiting factor. The best coupler pattern accuracy we can hope for (based on evaluation of present-day pattern-generation technology) is a scale error of 0.0002 inch in 20 inches (the length of the coupler). or 10 microinches per inch. Therefore, it will be necessary to incorporate some method of scale correction, preferably a method that can be used also to correct for temperature changes. The scale of this variable correction term would be adjustable to take account of the difference between the coefficient of thermal expansion of the Phasolver substrate and the object(s) being measured.

Table 2-1. Potential Pattern and Mechanism Errors

CAUSE	TYPE	COMMENT
Coupler scale error	Linear with distance.	Similar to temp. error. (See para. (5).)
Temp. coefficient of expansion	Linear with distance and temperature rise.	Closed-loop correction possible. (See para. (5).)
Driver waveform error	Limits best possible elec. balance.	Does not increase with distance measured. Existing patterns indicate an error of ± 0.25 micron.
capacitance fringing	Same as waveform error.	Can interact with misalignment. Magnitude unknown, but will be determined by analysis.
Misalignment of guide with pattern	Error within the p-p. Not necessarily a linear dependence on distance. May not be minimum at zero.	Best position probably controlled by the position in which elec. balance is made.
Random errors in spacing of driver and coupler pole-pairs	We have never proved any effect of this type of error.	Theoretically should appear as product with another error. Analysis will verify effect of averaging over many pole-pairs.
Error in phase displacement in pattern	Limits best possible elec. balance, causing fourth harmonic within a p-p.	Is a product with the amplitude difference introduced to compensate. The analysis and experimental verification of this error component source is underway.

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(5) Scale Correction. - The design goal is 4096 counts per pole-pair. An error in the scale of the device will stretch or shrink all of the pole-pairs alike. If the frequency of the driving signal is fixed, the modulus is unchanged, and each count represents a different length in proportion to the scale of the entire device. However, the modulus (the number corresponding to one pole-pair) is the product of the oscillator frequency and the time associated with the maximum phase shift. Therefore, a fine adjustment of the oscillator frequency could be made changing the modulus. Suppose, for example, that the original pattern was 0.1 percent too long. Each count would not represent the nominal distance but would represent 0.1 percent more than it should. By increasing the oscillator frequency 0.1 percent, the new, longer pole-pair would have associated with it a new, larger number, and each count would be correct.

Temperature correction could be applied by a similar method; but since this error is not a fixed scale factor, it would require a servo system or rapid and frequent manual recalibration.

One compensation in technique is to use a frequency-adjustment circuit so that an error in pattern scale can be corrected, using gage blocks as a reference. The correction will be made at some operating temperature and will automatically take care of temperature effects at that temperature. During the tests, temperature will be visually monitored and adjustments made as required.

c. ELECTRONIC DESIGN. - In order to conserve time and money in fabricating the electronics required for this program, we propose to build only the driving electronics for the Phasolver. The digitizing will be performed by commercial electronic counters such as the Beckman Berkley Model 7370 EPUT Meter.

The required resolution of this system in the fine channel is 1/4096. This places stringent requirements on the driving electronics. The filters must have a phase-stability of 50 nanoseconds, maximum. The buffer, driver amplifiers, and preamplifier must have a maximum gain and phase stabilities of 0.005 percent and 50 nanoseconds, respectively. The zero-crossing detector must have a maximum uncertainty or jitter of 50 nanoseconds. These figures are based on a total maximum error of 0.1 microsecond allowed in the electronics. Laboratory phase-stability measurements of these circuits indicate that we are meeting these requirements at a constant temperature. In fact, some of the circuits (such as the drive amplifiers, buffers and zero-crossing detectors) approach these requirements over a temperature range of 0° F to 150° F.

This stability must be maintained at all room ambient conditions which may be experienced during the program. Therefore, the electronics will be housed in a temperature-controlled environment having a maximum variation of $\pm 2^\circ$ C. A minimum of engineering is required to adapt this circuitry to the linear Phasolver study program.

2-8 TRAVELS EXCEEDING 10 INCHES. - The design of a linear Phasolver for the measurement of linear movement in excess of 10 inches presents problems which are not encountered in Phasolver applications for a more limited range.

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a. PATTERN GENERATION. - The length of the driver pattern is determined by the requirement for averaging and not by the length of travel.

In order to resolve the ambiguity of the fine track. it will be necessary to utilize a coarse track. Our experience with a 30-inch circular Phasolver (256 x 1), which has a coarse track of approximately 22.5 inches in diameter, indicates that a single coarse track will give acceptable results for measurements as great as 70 inches. This track would require an increase in the width of the driver of no more than 2 inches.

The coupler would also require a coarse track. The minimum width of this pattern for a 70-inch length would be 4 inches. To achieve averaging and avoid end effects, the total travel would be limited to approximately 11 inches less than the length of the coupler. Therefore, in an extrapolation of the feasibility model to 59 inches of travel, it can be assumed that no improvements in the patterns or electronics will be required. The design of a Phasolver for travels in excess of 59 inches would require an increase in the width of the coarse track of not more than 2 inches for each additional 70 inches of travel.

An extensive survey was conducted which located a processor, [redacted] STAT

STAT [redacted] who has a linear ruling engine capable of scribing a pattern up to 78 inches in length. In addition, they have a hydrofluoric-acid etching tank capable of accommodating forms as large as 80 inches square. The ruling engine is reputed to be accurate within ± 0.0002 inch over its entire range. Our investigation indicates that this is the largest equipment of this kind in this country. Because this equipment is available for processing our patterns, splicing of the glass substrate will not be necessary if the work does not exceed 78 inches of travel.

b. WAYS. - The use of glass alone for coupler plates exceeding 24 to 30 inches in length appears to be impractical. It will probably be necessary to laminate glass of convenient thickness to a granite straightedge. The use of granite will probably be seriously considered by the designer of the machine itself because no machine tool is capable of cutting metal ways to the required accuracy.

Solving the problems presented by the interface between a linear Phasolver and the machine it is tracking will require close collaboration between the designers of the Phasolver and the designers of the measuring machine. This will be of the greatest importance during the early stages of development.

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SECTION 3

PROGRAM ORGANIZATION

3-1. GENERAL

The responsibility for successful execution of this program will be assigned to the Systems Engineering section within the Engineering Department of the [redacted] STAT
STAT [redacted] Figure 3-1 shows the organization of the Engineering Department.

The Systems Engineering section is presently responsible for 1) the engineering development of the ±5-arc second-accuracy 2-axis Phasolver system which is being used as the gimbal-position pickoff on the Orbiting Astronomical Observatory star trackers for General Electric Company, MSVD, and 2) the engineering development of the ±3.6 arcsecond 2-axis Phasolver system which is being used as the azimuth and elevation axis transducers on the Haystack radio-telescope antenna for North American Aviation, Columbus, Ohio.

3-2. ASSIGNMENT OF PERSONNEL

STAT [redacted] proposes to assign engineering personnel to the program who have comprehensive knowledge and experience in the problems presented by this project. (See figure 3-2.) Successful completion of the program will be assured by utilizing the skills gained through active participation in the development of Phasolver devices and applications.

In addition to the effort provided by the project group, [redacted] STAT
STAT [redacted] can draw upon the wide scope of experience of its engineering staff to aid in the solution of problems presented by the task.

3-3. PERSONNEL RESUMES

The following resumes describe the experience and background of the personnel who will be directly responsible for the tasks involved in the project.

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SECTION 4

PROGRAM SCHEDULE

4-1. PROGRAM SCHEDULE

a. PHASE I. - It is expected that Phase I will require 12 weeks from authorization to proceed to the completion of this phase. A schedule, showing the tasks that will be performed, is shown in figure 4-1.

b. PHASE II. - Phase II is expected to last for 48 weeks and will be performed concurrently with Phase I. The tasks to be performed, and the time required for each task, are shown in figure 4-2.

4-2. MANHOURS

Manhours estimated for execution of both Phase I and Phase II, by labor classification, are provided as a separate enclosure attached to the letter of transmittal.

TASK

1 Rework Driver

2 Design Fixture for Coupler

3 Fab. Fixture for Coupler

4 Design & Coordination of Final Set-up

5 Testing

6 Report

7 Electronics Package

Countdown Chain Design

Procurement of Parts

Wiring and Stuffing

Test

8 Monthly Progress Reports

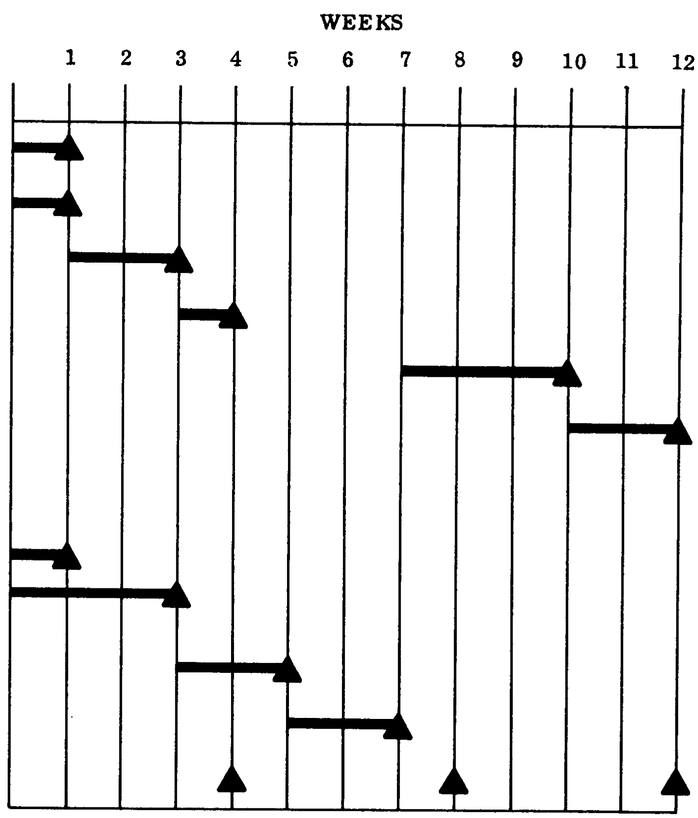

Figure 4-1. Proposed Program Schedule, Phase I

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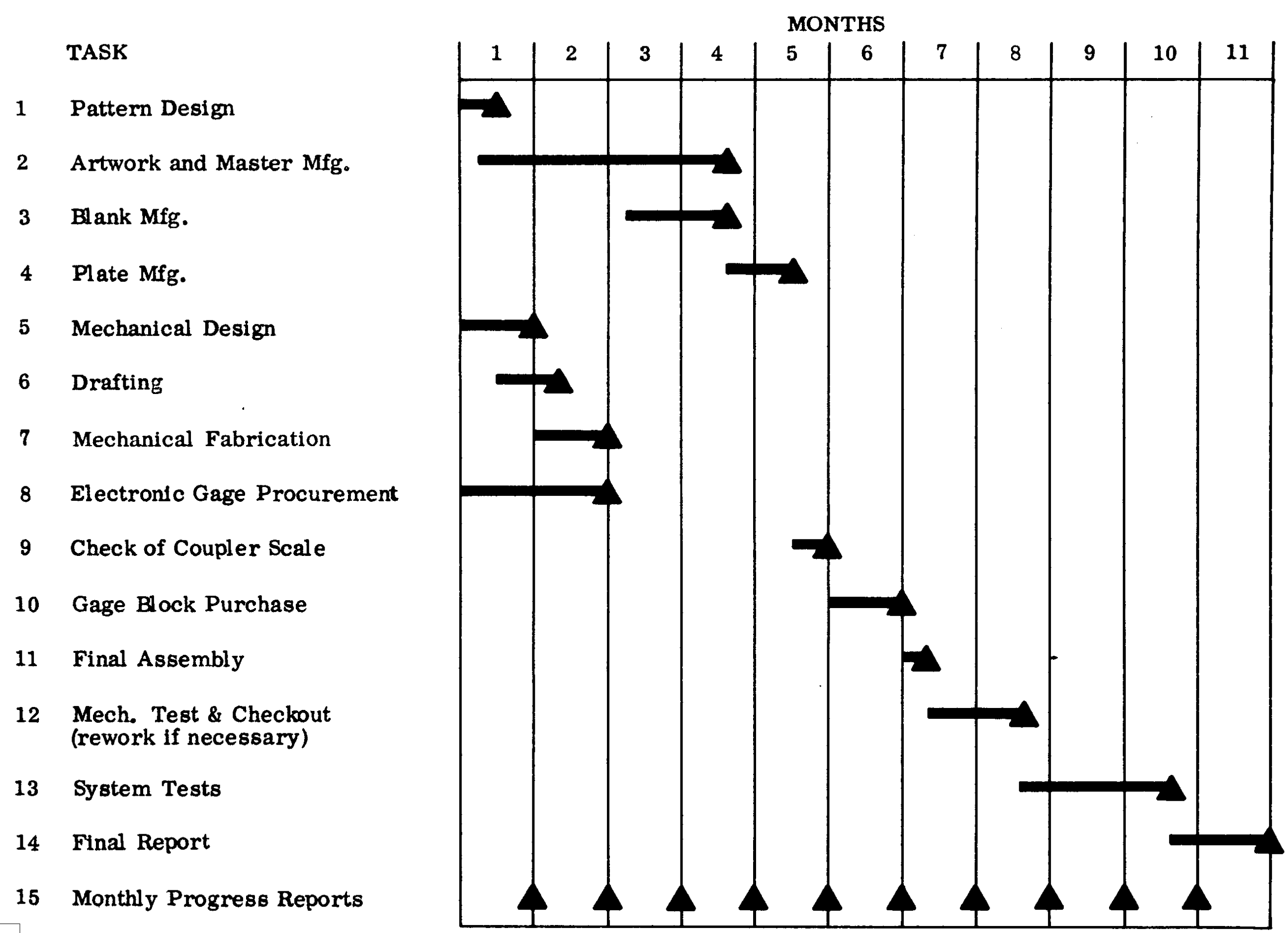

Figure 4-2. Proposed Program Schedule, Phase II

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SECTION 5

RELATED EXPERIENCE

5-1. COMPANY BACKGROUND

During the past decade, [redacted] has been engaged in the development and refinement of Phasolver applications under both company-sponsored and military contract programs. Although much of the past effort has been directed toward application of the Phasolver for measuring rotary motions, the same principles are involved in using the Phasolver to measure linear motion. STAT

In 1953, while operating the Data Reduction Center, Flight Determination laboratory, at Holloman Air Force Base, [redacted] engineers discovered that the available means for measuring shaft position did not meet the requirements for greater and greater accuracy. Therefore, development of a completely new system became necessary. STAT

STAT [redacted] scientists and engineers carefully studied the entire field of shaft digitization techniques and concluded that breakthroughs in both the fundamental approach and the manufacture of electronic components would be required to achieve the required accuracy. Severe limitations were imposed by the necessity for locating the basic transducer where it would be exposed to extremes of environment and almost inaccessible for maintenance.

To achieve a practical design, the following conditions had to be satisfied:

a. The transducer must not include elements which wear, burn out, or require frequent maintenance.

b. The transducer must be relatively insensitive to environmental changes.

c. A continuously variable zero adjustment must be available.

d. The transducer must indicate position as an unambiguous signal which is not dependent upon counting techniques. This is to ensure accuracy of data both before and after any interruption of operation, such as a momentary power failure.

An exhaustive study was made of shaft position digitizing methods, and the following conclusions were drawn:

a. Conversion of shaft rotation to changing electrical phenomena is the only method of achieving a resolution of one part in a million, or better.

b. The system must not depend on the measurement of absolute values, only on relative values of the electrical phenomenon.

c. The system must take advantage of the electrical phenomenon which can be most accurately measured, for example, a time or phase displacement.

All systems in use at that time were rejected. A development program was initiated to evolve a shaft-position digitizing system which met all requirements, taking advantage of the study conclusions. The result was the Phasolver system, which depends upon the measurement of a relative phase displacement produced by shaft rotation.

5-2. PHASOLVER SYSTEM APPLICATIONS

The Phasolver is being used in the instrumentation of a 60-foot antenna for the Naval Electronics Laboratory in San Diego, California. Another application is the instrumentation of a 125-foot-diameter antenna for Project Haystack. In this application, the Phasolver provides azimuth and elevation position information, compares it with command information, and generates error signals to the antenna servo system.

A "flyable" Phasolver system (figures 5-1 through 5-4), employing miniaturized electronic circuits, is being built for an orbiting astronomical observatory (OAO). This system will provide information which locates the angular position of six star-trackers within each satellite. In conjunction with the OAO program, a laboratory system has been designed and fabricated to facilitate prelaunch checkout of the star-tracker equipment.

Another application of the Phasolver is the Redstone Radio-telescope Digital Control and Data Handling System. This program entailed system responsibility for instrumentation of an 84-foot-diameter radio-telescope antenna located on Madkin Mountain, near Huntsville, Alabama. This digital control and data handling system accepts command-pointing information, on paper tape, from a space track center or from other tracking stations. Information, supplied in geocentric or local azimuth-elevation coordinates, is processed and converted to local azimuth-elevation coordinates by a coordinate converter. In addition, the system, which uses a 30-inch disk Phasolver (figure 5-5), can accept command information in terms of hour, angle, right ascension, and declination of star-tracking missions. The system compares command information with actual antenna position and generates servo error signals to position both azimuth and elevation axes to an accuracy better than 0.01 degree. Also provided is the actual antenna position in terms of local azimuth-elevation, geocentric and hour angle-right ascension-declination coordinates. These coordinates, together with universal time, are recorded by paper-tape perforators and high-speed line printers. These output devices also accept the record data from various peripheral equipment, including frequency counters and multiplexed analog-to-digital conversion systems. The output data format can be selected through the use of an output matrix and plug board.

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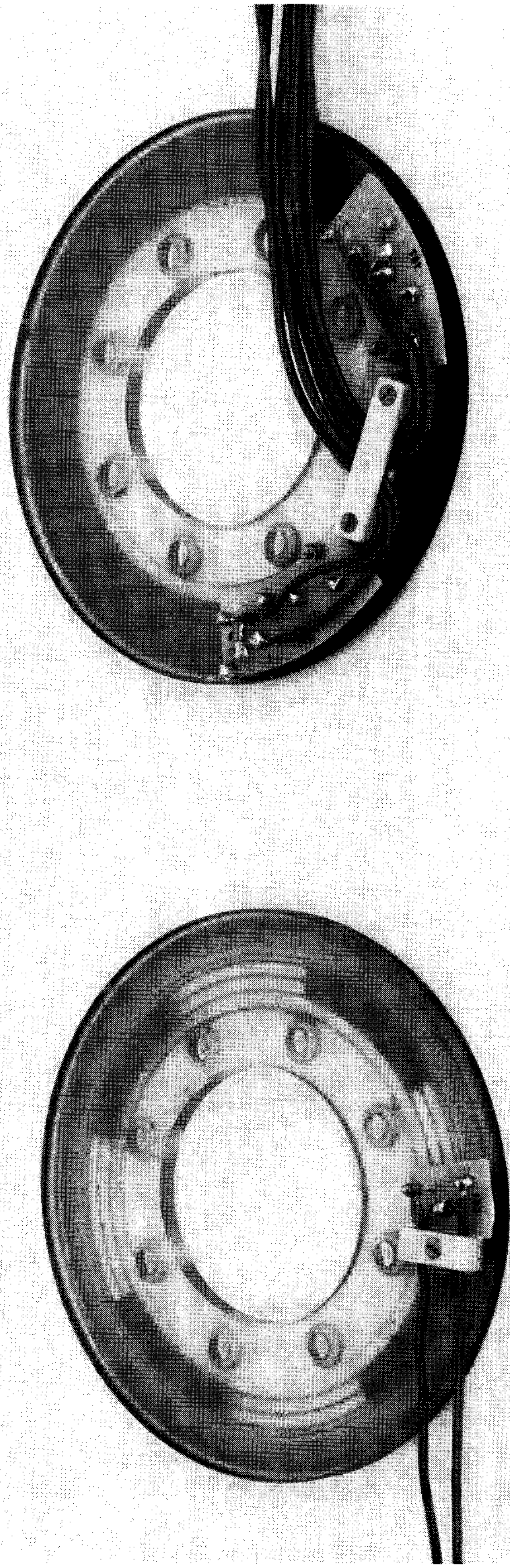

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Figure 5-1. 256 x 4 Pole-Pair Driver and Coupler, 4-1/2 Inch Diameter Disks Disks

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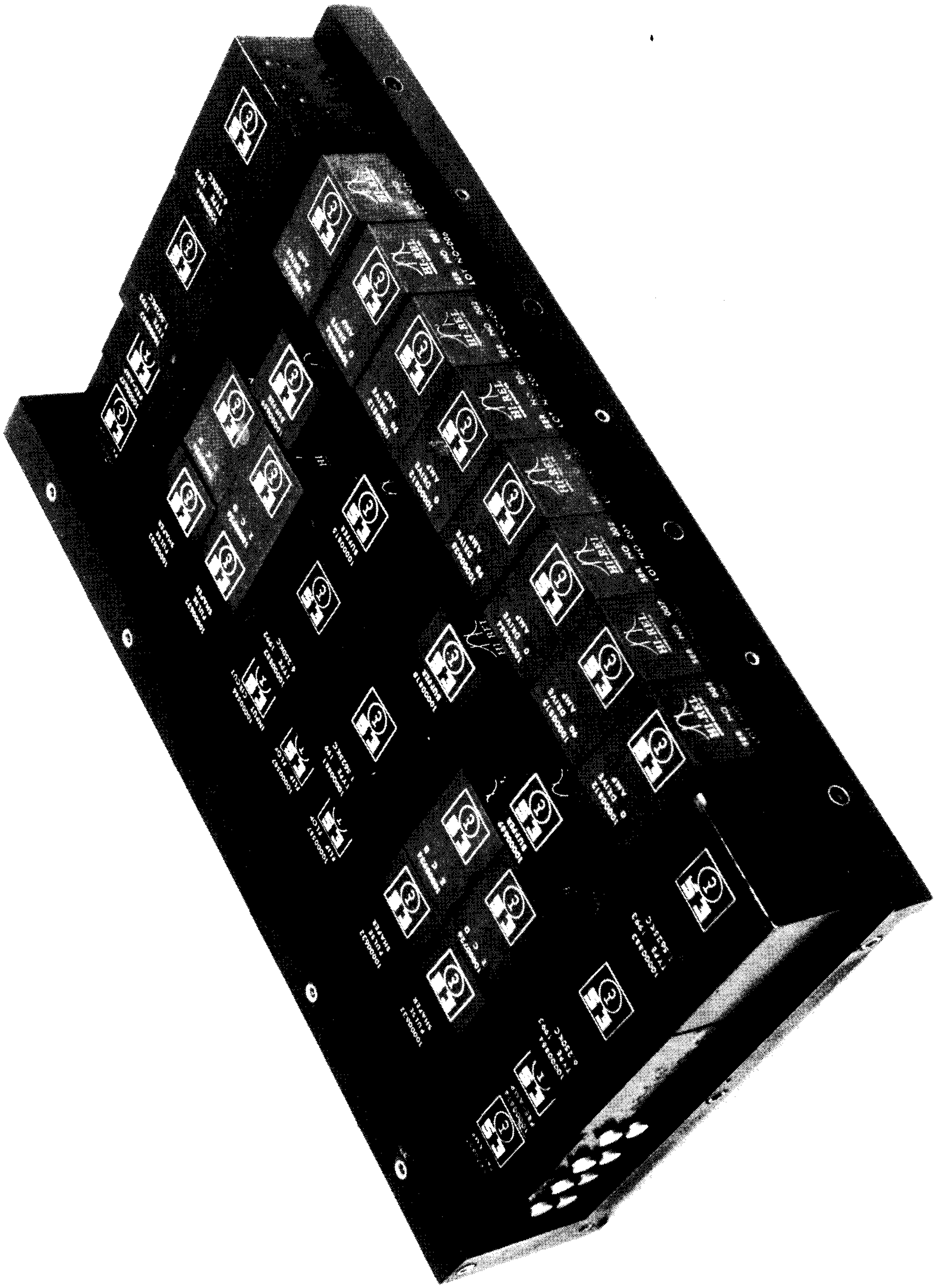

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Figure 5-2. OAO Phasolver, Electronics Subsystem, Top View

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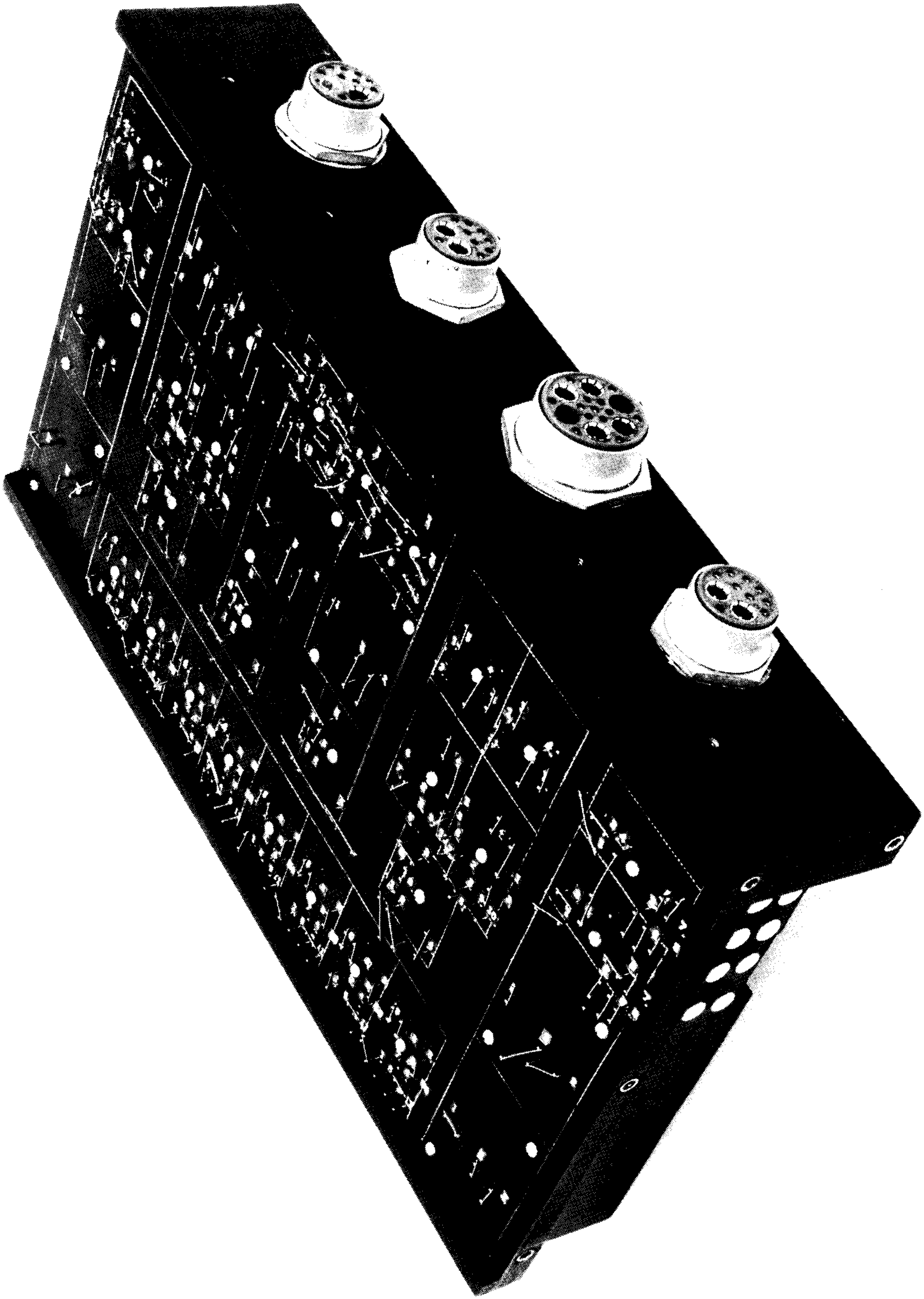

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Figure 5-3. OAO Phasolver, Electronics Subsystem, Bottom View

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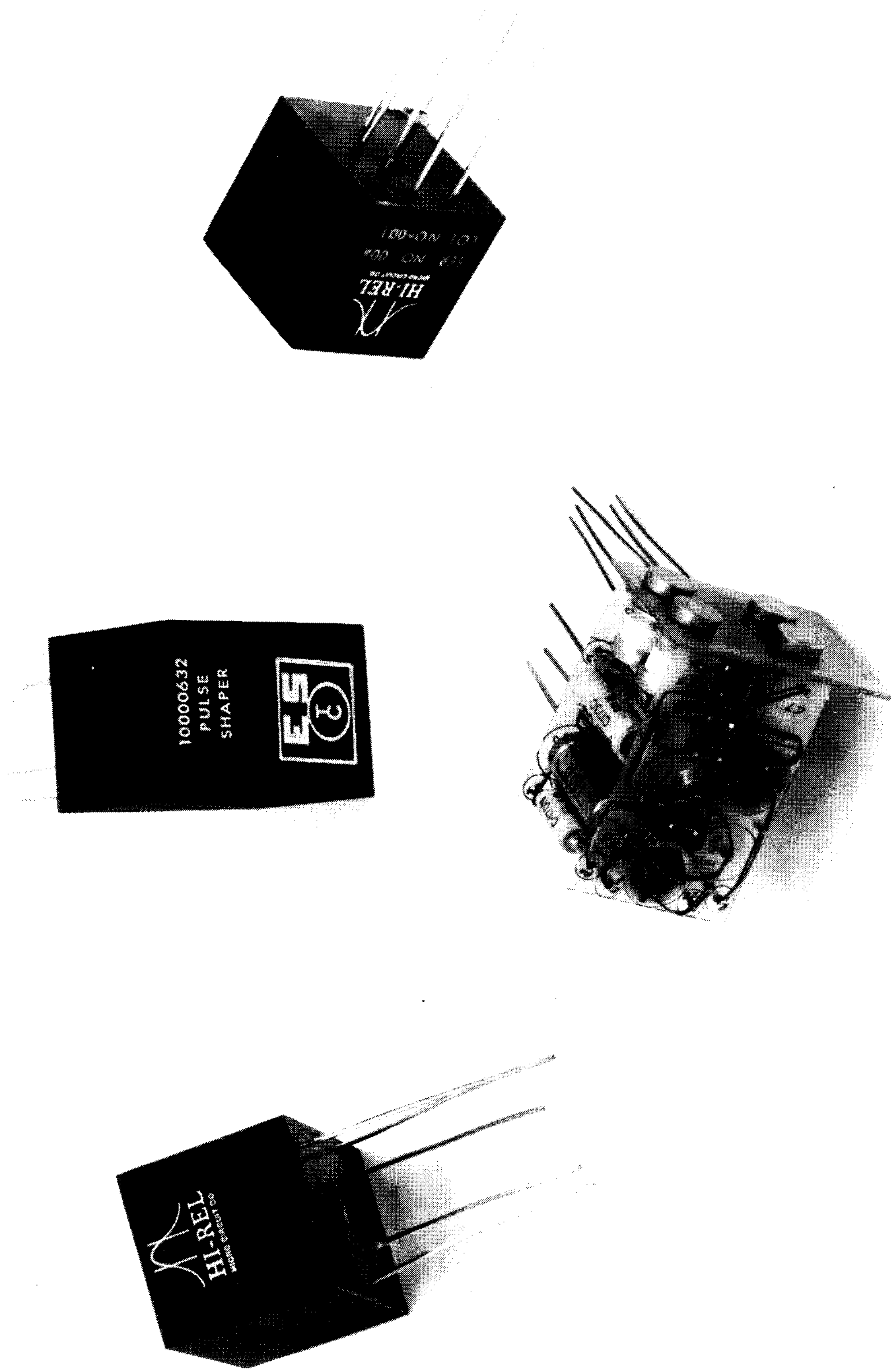

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Figure 5-4. Welded Circuit Modules, OAO Phasolver Electronics Subsystem

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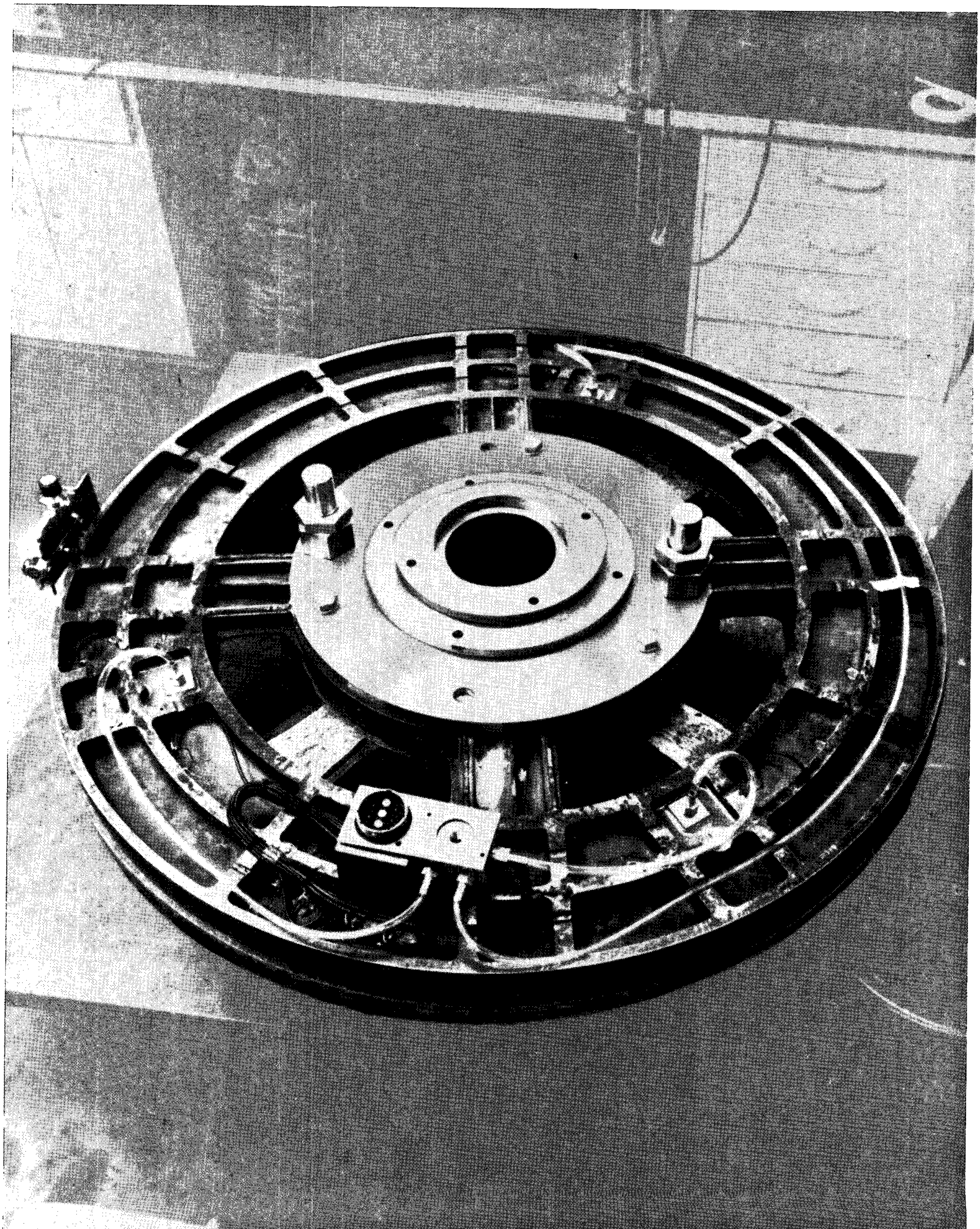

Figure 5-5. Redstone 30-Inch Dish Phasolver

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A Phasolver system has been delivered to Edwards Air Force Base, California, where it has been applied to the ASKANIA Cinetheodolite (See figures 5-6 and 5-7.) This system has been successfully applied to the problem of position-encoding for both the azimuth and elevation axes to an arc accuracy of ± 6.0 seconds of arc. The purpose of this system is to eliminate the necessity for making dial readings for each frame of film exposed by the cinetheodolites.

5-3. RELATED GOVERNMENT CONTRACTS

Following is a representative list of government contracts for Phasolver systems:

Contract No.	Description

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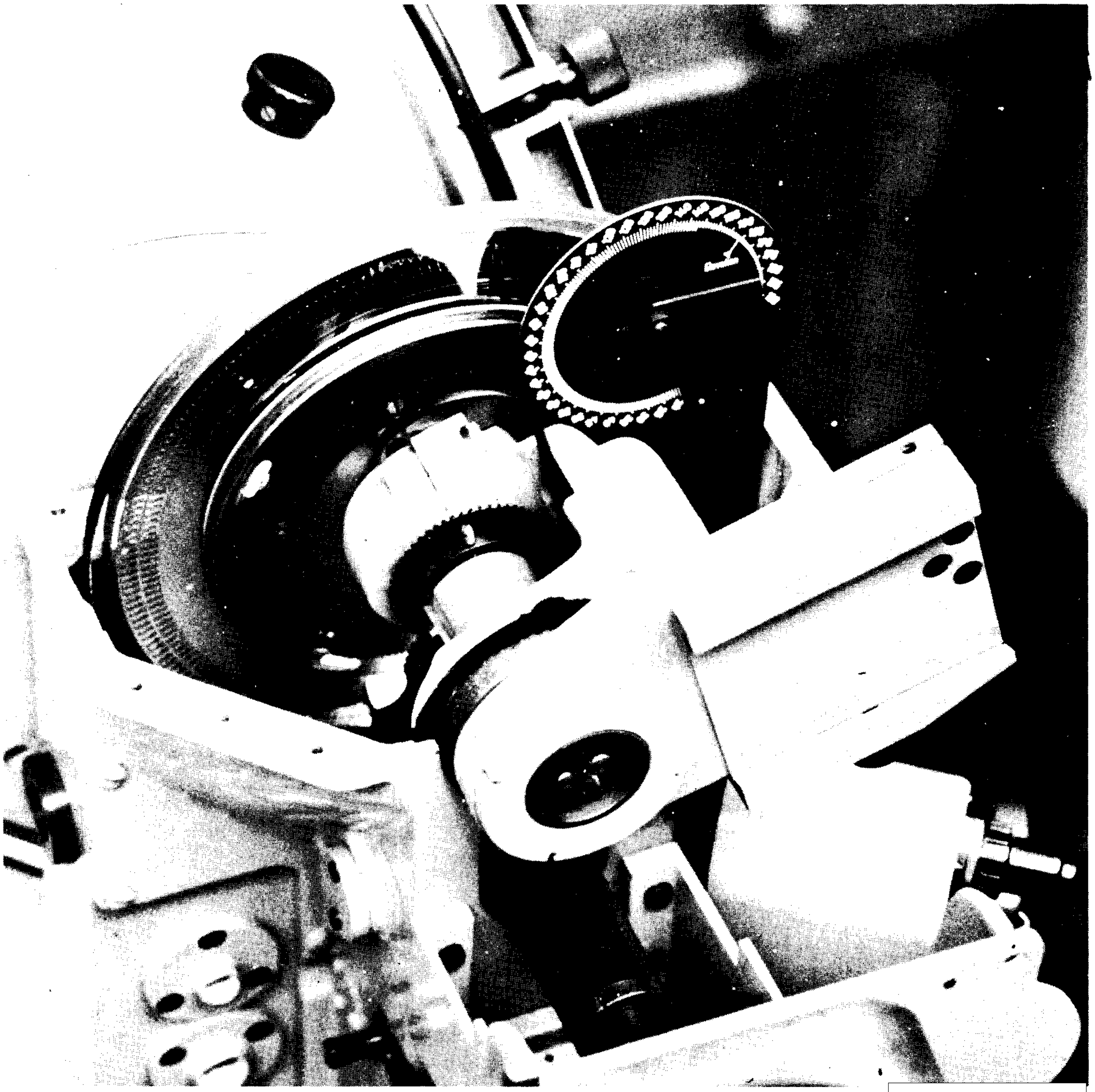

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Figure 5-6. ASKANIA Cinetheodolite Phasolver

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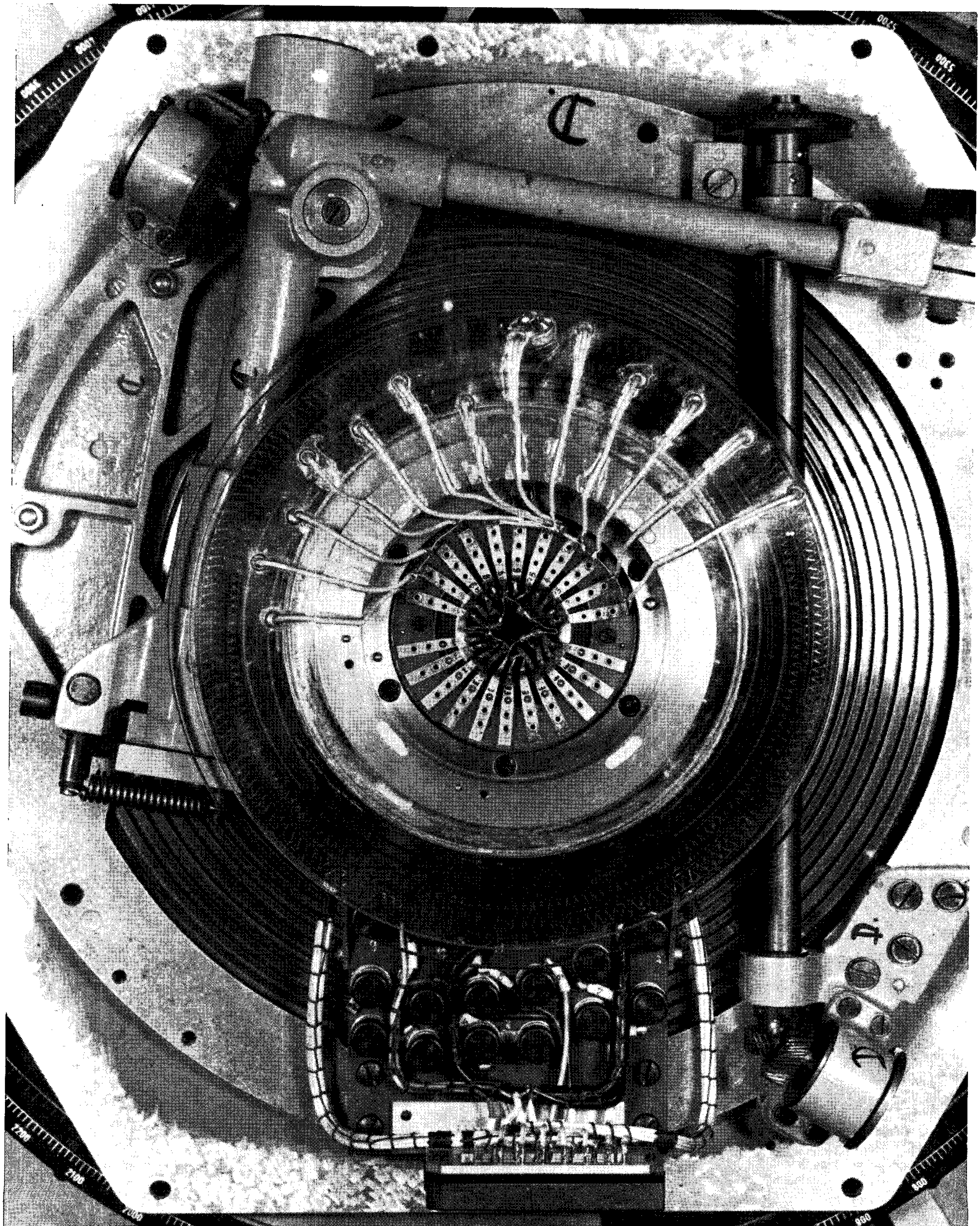

Figure 5-7. ASKANIA 8-Inch Disk Phasolver

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APPENDIX A

LAYOUT OF LINEAR PHASOLVER

A-1. GENERAL

Figure A-1 shows the mechanical layout of the proposed linear Phasolver to be developed in Phase II of the program.

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